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VOLTAGE LOCKING IN TWO COUPLED MICROBRIDGE JOSEPHSON JUNCTIONS.(U)
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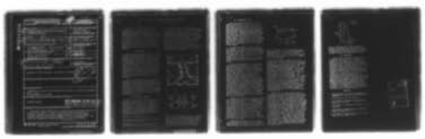

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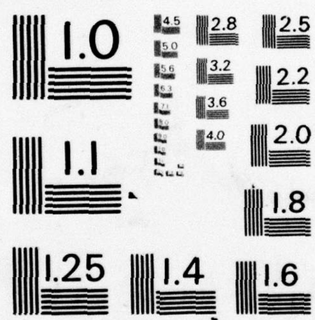

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Voltage locking, defined as the production of an identical non-zero DC voltage in the absence of external microwave radiation across each Josephson junction of an array, has been observed in two microbridge Josephson junctions separated by a 2μm wide strip of superconductor. The voltage and temperature dependence of the locking is described.

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VOLTAGE LOCKING IN TWO COUPLED MICROBRIDGE JOSEPHSON JUNCTIONS*

D. W. Jillie, J. E. Lukens, Y. H. Kao†

ABSTRACT

Voltage locking, defined as the production of an identical non-zero DC voltage in the absence of external microwave radiation across each Josephson junction of an array, has been observed in two microbridge Josephson junctions separated by a 2μm wide strip of superconductor. Voltage locking occurs when the bridges are biased with the current flowing in opposing directions thru the bridges and out the strip connecting them. The voltage across each bridge can be pulled over 1μV until each bridge displays an identical non-zero voltage, with the total voltage across both bridges equal to zero. Full locking, as defined above, is observed in excess of 40μV. The voltage and temperature dependence of the locking is described.

I. INTRODUCTION

Josephson junctions have excited a great deal of interest in recent years for use as microwave emitters, detectors, mixers and parametric amplifiers[1]. In particular, series arrays of thin-film microbridge Josephson junctions are being investigated due to their ruggedness and ease of fabrication, their broad band capabilities and their superior impedance matching characteristics. However, for many applications it is necessary to use coherent arrays.[2,3,4,5] A coherent array is one in which the frequency and phase of the AC Josephson oscillation is the same in each bridge of the array. Our previous work with series arrays of microbridges indicates that such an array is not normally coherent, however with the application of sufficient microwave power it is possible to synchronize the bridges to the applied frequency.[5]

In order to understand why series arrays are not normally coherent we have been investigating the interactions between two microbridges in detail. We have fabricated two submicron indium bridges separated by as little as 1.0μm of superconducting film, capable of being independently current biased, and their individual voltages monitored. This arrangement has allowed us to study the interactions between two microbridges both with and without external radiation and determine if the possibility exists for fabrication of a coherent array.

II. EXPERIMENTAL TECHNIQUES

Figure 1a shows an indium sample similar to those used for these experiments. The individual microbridges are always < 1μm square and typically 1000 Å thick. The fabrication and general characteristics of our microbridges has been described in detail elsewhere[5]; we would like to reiterate the fact that electron beam lithography permits us to fabricate two submicron bridges with various separations and a reasonably well defined geometry. The experimental results described here are for bridges with a 2μm separation.

A typical measurement circuit is shown schematically in Fig. 1b. Eight superconducting leads are provided, and measurements are made using two four-terminal circuits allowing the bridges to be independently current biased and the voltage across either or both bridges to be monitored. It is also possible to apply current between any two of the four current leads and monitor the voltage across any two of the four voltage leads. This flexibility has proven very useful in understanding the observed interactions. Measurements are made in a fully shielded dewar. Cryogenic low pass filters effectively protect the bridges from external noise. The temperature is measured by a germanium thermometer, with electronic feedback used to regulate the temperature to within a few μK.

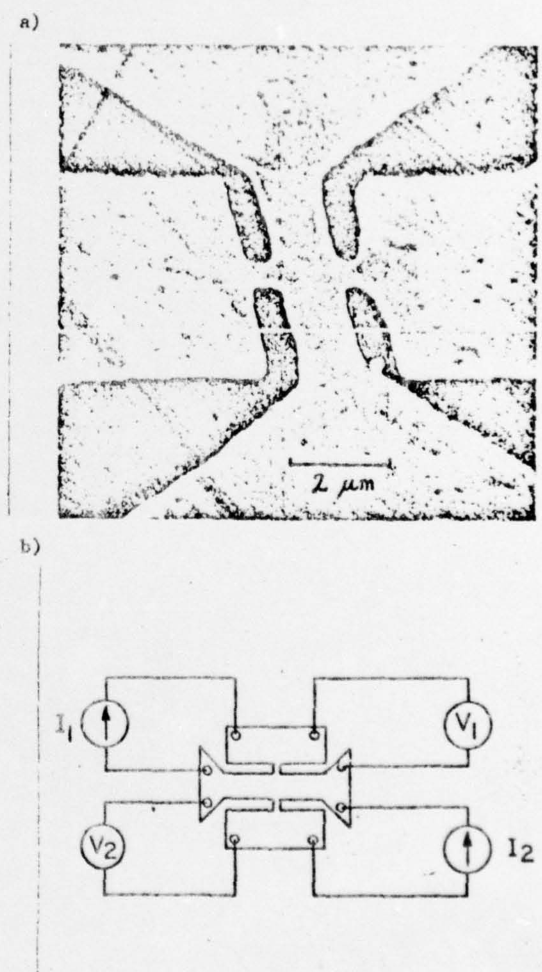

Fig. 1. a) SEM micrograph of a sample, tilted 45° to the beam, showing typical geometry. The light areas are 1000 Å In film. The bridge separation here is 1.2μm. b) A schematic diagram of the measurement circuit. For AC measurements ≈ 0.1μA AC current is added to the DC current and the voltage is monitored with a lock-in amplifier.

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III. EXPERIMENTAL RESULTS

These coupled microbridges exhibit a great number of interactions, as manifested by the distortion of their I-V curves. Some of our initial observations have been described elsewhere[6], here we wish to focus upon our observation of voltage locking, since that relates directly to the fabrication of coherent arrays. An example of voltage locking is shown in Fig. 2a. The current thru bridge 2 is fixed at a value slightly above its critical current and current is swept in the opposite direction thru bridge 1 and out the superconducting pad separating the two bridges. V_1 and V_2 are monitored as I_1 varies. Note that the two voltages are equal from $I_1 \approx 83$ to $87\mu A$, with V_2 being pulled in lock with V_1 over a range of $1\mu V$, even though the current thru bridge 1 is held constant.

In a practical array both currents would be swept together. Thus the $1\mu V$ pulling observed with I_2 fixed implies that the bridges would stay locked over a wide voltage range. We have, in fact, observed continuous locking from 0 to $40\mu V$ when both currents are swept together. Since the opposing current bias is essentially a parallel DC connection of the bridges it would be simple to maintain nearly equal voltages across all bridges with the external bias circuit, thus improving the locking range even further.

To check the completeness of the locking with greater precision a $0.1\mu A$ AC signal is added to I_1 only and the voltages monitored with a lock-in amplifier. The result is dV_1/dI_1 and dV_2/dI_1, the slopes of the two curves in Fig. 2a. In addition, the total AC voltage (V_T) may be monitored. This is shown in Fig. 2b as dV_T/dI_1. During locking $dV_1/dI_1 = dV_2/dI_1$; since the voltages are in opposite directions this implies $dV_T/dI_1 = 0$. The decrease in dV_T/dI_1 in the locking region can be used as one measure of the strength of the interaction. Thus $dV_T/dI_1 = 0$ indicates complete locking, and the measurement of $\Delta(dV_T/dI_1)$ provides a gauge of the strength of the interaction, even though complete locking may not occur. As a further check upon the locking strength we increased the amplitude and frequency of the AC modulation current and monitored dV_T/dI_1 while sweeping I_1 through the locking region. We found that $dV_T/dI_1 = 0$ for a modulation corresponding to a voltage rate of change of 3mV/sec (or a frequency modulation of $\approx 1.5 \times 10^3$ GHz/sec). Higher modulation rates were not possible due to circuit limitations.

Voltage locking is observed both when the current flows thru the two bridges and out opposite sides of the interconnecting pad, or out only one side of the pad. In the latter case there is usually a voltage in the pad, and at sufficiently high current levels a pad voltage appears in the former case. The appearance of a resistance in the pad does not preclude observation of voltage locking between the two bridges. However, the pad voltage does add considerably to the complexity of the interactions observed, and in order to understand the locking interaction we have confined most of our recent observations to situations in which the pad remains superconducting. Thus the data in Figs. 2 and 3 were taken with no pad voltage.

We have found the voltage locking to be both voltage and temperature dependent. Typically full locking ($dV_T/dI_1 = 0$) is observed within some voltage range for temperatures ranging from T_c to about

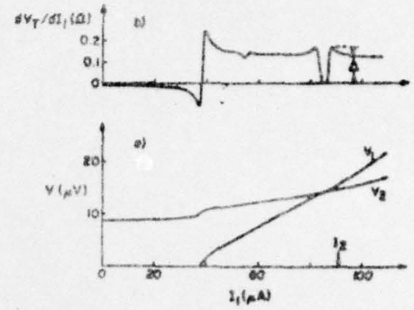

Fig. 2. An example of voltage locking between two microbridges. a) I_2 is fixed and both V_1 and V_2 are shown as I_1 varies. b) The total differential resistance of both bridges. Note that dV_T/dI_1 goes to zero in the locking region. $\Delta(dV_T/dI_1)$ is a measure of the locking strength.

0.98 T_c. Less complete locking interactions are observed down to $\approx 0.90\ T_c$, however at this point the strength of the interaction has decreased considerably. The variation of locking strength with voltage at two different temperatures is shown in Fig. 3. At $T/T_c = 0.992$ full locking is observed from 13 to $20\mu V$, the peak of the interaction strength. At the lower temperature the peak at $30\mu V$ does not correspond to full locking. Note that the main peak has moved to a higher voltage at the lower temperature. Also note the oscillation in the locking strength. This oscillation was particularly pronounced in this sample, but has been observed to a lesser degree in all other samples tested. However, with more strongly coupled samples at an appropriately chosen temperature, continuous full locking has been observed from 0 to $40\mu V$. We believe that this behavior may be related to a frequency dependent phase shift in the locking interaction. Investigation of this point is continuing. The locking interaction does persist to higher voltages than shown here, but a pad voltage develops at the same time.

A microbridge at a finite voltage supports a supercurrent and a normal current, both oscillating at the Josephson frequency. The observed behavior of the voltage locking interaction is consistent with the assumption that pulses of the normal current diffuse across the pad separating the bridges and interact with the other bridge. In the opposed current situation the normal current would tend to increase the instantaneous supercurrent in the affected bridge, and could trigger an impending phase slip. Consistent with this idea is the fact that locking is never observed with currents flowing through the bridges in series. This is because, in the series case, the normal current diffusing from the other bridge delays the onset of a phase slip by reducing the supercurrent, which moves to compensate for the diffusion of the quasiparticles and maintain steady current flow. This model is supported by the fact that stronger voltage locking is observed when the pad resistance is higher, since this results in a larger fraction of the normal current flowing thru the other bridge. We are presently working on a dynamic model of the interaction between the bridges due to the normal currents.

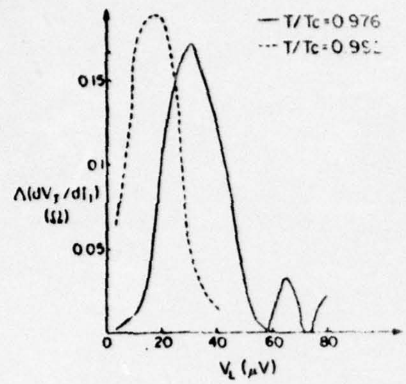

Fig. 3. Variation of the locking strength with voltage at fixed temperature. This figure illustrates the oscillatory nature of the locking with voltage, and the movement of the maximum locking strength peak to higher voltages as the temperature is reduced.

IV. CONCLUSIONS

We have observed an interaction between two microbridges that acts to lock the voltages of the bridges to a single common value. Locking is observed only when the DC current flows in opposite directions thru the two bridges and out the connecting superconducting pad. Continuous full locking has been observed in excess of 40μV under appropriate conditions. No locking is observed when current flows in the same direction thru the two bridges (series biasing); in fact the interaction tends to force the voltages apart in this case. Series arrays of microbridges can be forcibly synchronized with the application of sufficient microwave power, but for close separations (< 5μm) the locking interaction works against this synchronization; however when current is swept thru the two bridges in opposing directions (parallel biasing) perfect voltage locking can be maintained without any external microwave radiation. It remains to be demonstrated that the Josephson oscillations are in phase before full coherence may be claimed. We are presently working on ascertaining the exact nature of the locking interaction.

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